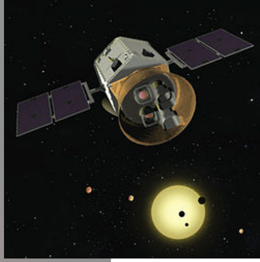


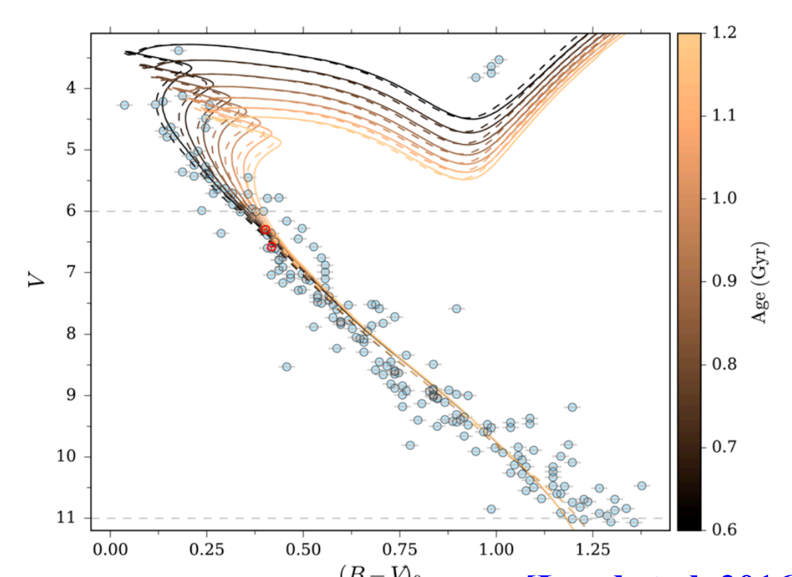
Stellar modeling and asteroseismology: status and current issues (solar-like stars)

Savita Mathur

Instituto de Astrofísica de Canarias

Getting stellar fundamental parameters

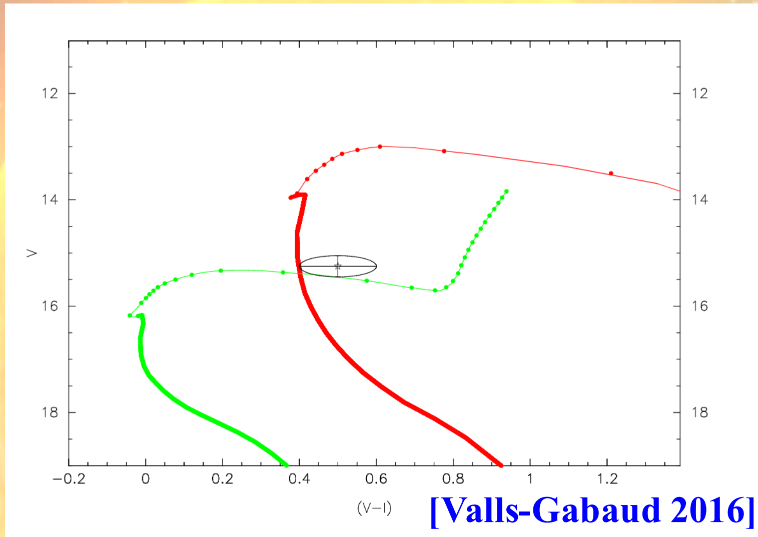
- Isochrone fitting based on:
  - Color
  - Magnitude
  - T_{eff}
  - logg
- Provide:
  - Radius, mass, age
  - Structure
- Impact on many fields:
  - Galacto-archeology
  - Exoplanet characterization
  - Characterizing field/cluster stars
  - …



[Lund et al. 2016]

Issues

- Degeneracy problem when fitting the isochrones:
  - Which isochrone is the correct one?



- Uncertainties due to lack of observational constraints
- Ill-constrained physical processes

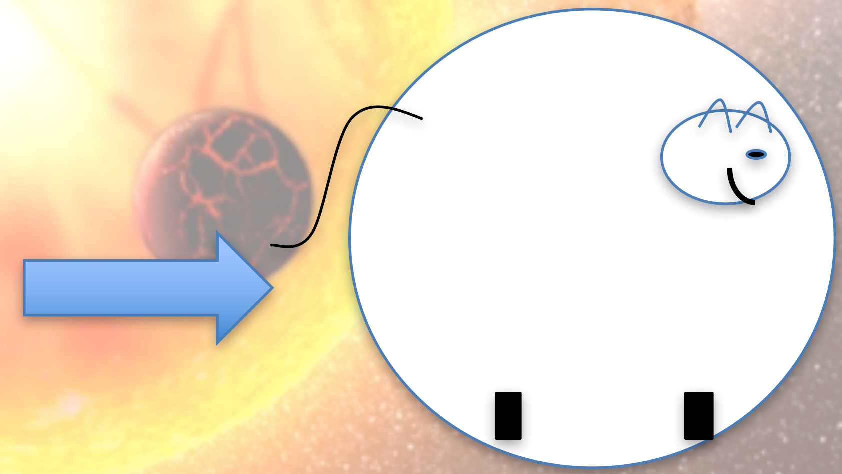
From the Sun

Standard Solar Model

Standard solar model

From Wikipedia, the free encyclopedia

The **standard solar model** (SSM) is a mathematical treatment of the Sun as a spherical ball of gas (in varying states of ionisation, with the hydrogen in the deep interior being a completely ionised plasma). This model, technically the spherically symmetric quasi-static model of a star, has stellar structure described by several differential equations derived from basic physical principles. The model is constrained by boundary conditions, namely the luminosity, radius, age and composition of the Sun, which are well determined. The age of the Sun cannot be measured directly; one way to estimate it is from the age of the oldest meteorites, and models of the evolution of the Solar System.[1] The composition in the photosphere of the modern-day Sun, by mass, is 74.9% hydrogen and 23.8% helium.[2] All heavier elements, called *metals* in astronomy, account for less than 2 percent of the mass. The SSM is used to test the validity of stellar evolution theory. In fact, the only way to determine the two free parameters of the stellar evolution model, the helium abundance and the mixing length parameter (used to model convection in the Sun), are to adjust the SSM to "fit" the observed Sun.



Standard Solar Model

- Precise description of solar interior as inferred from helioseismology and solar neutrinos
- Starts from pre-main sequence
- Matches: L, R, and surface metalicity
- Physical processes included:
  - Convective and radiative transport
  - Chemical evolution
  - Microscopic diffusion (gravitational settling major factor)
- Constitutive Physics:
  - Equation Of State
  - Opacities
  - Convection treated following mixing length theory
  - Grey atmosphere

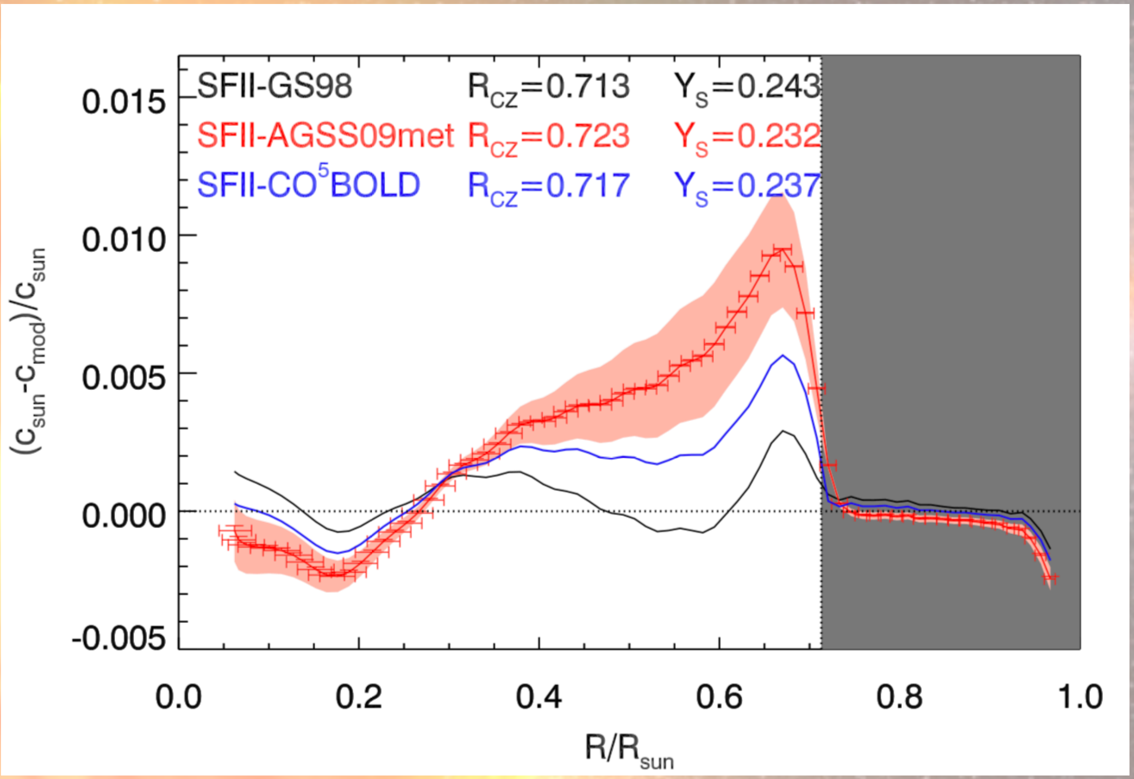
Solar abundances

- From spectroscopy of the solar photosphere
- In the 90's
  - Z/X=0.0245 **[Grevesse & Noels 1993]**
  - Z/X=0.023 **[Grevesse & Sauval 1998]**

- Introduction of 3D-RHD models
  - leads to large reduction compared to the previous measurement
    - Z/X=0.0180 **[Asplund et al. 2009]**
    - Z/X=0.0209 **[Caffau et al. 2011]**

Solar abundance problem

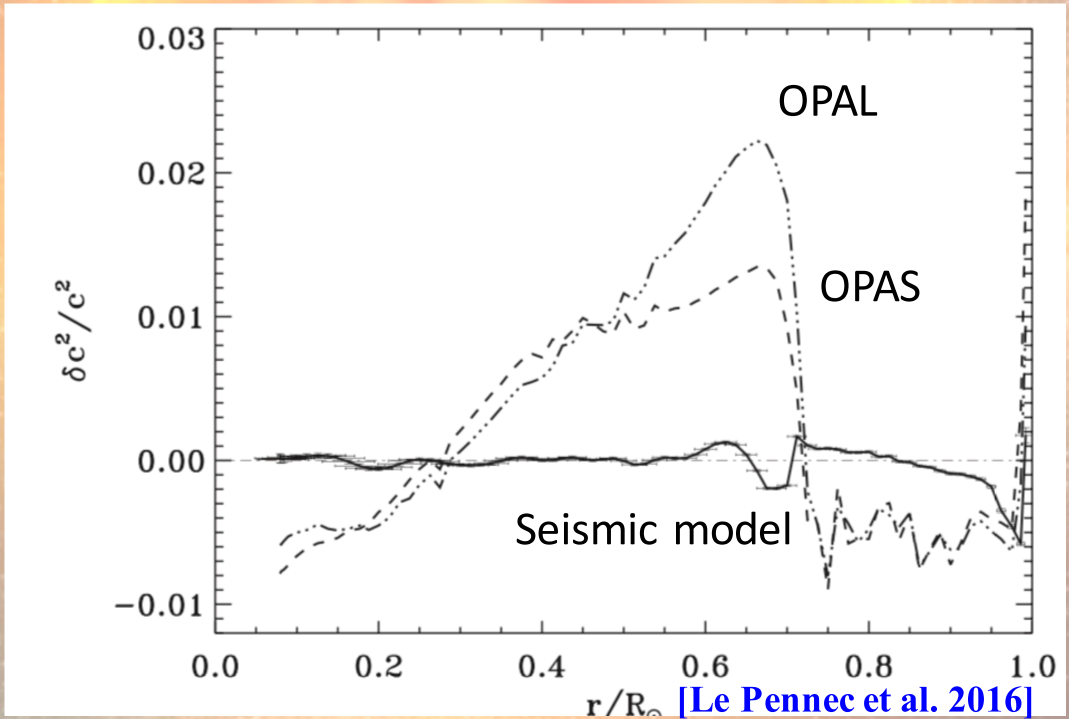
- Helioseismology
  - Sound speed profile derived from frequencies
  - Larger discrepancy between the models and the observations



[Serenelli et al. 2016]

Opacities

- Effect of changing the opacity mimics the change of metallicity
- New opacity tables from OPAS [Blanchard et al. 2012]
  - Computed with finer grids in T, Z
  - Differences of ~6% with OPAL tables.
- Reduces slightly the discrepancy



[Le Pennec et al. 2016]

To the Stars

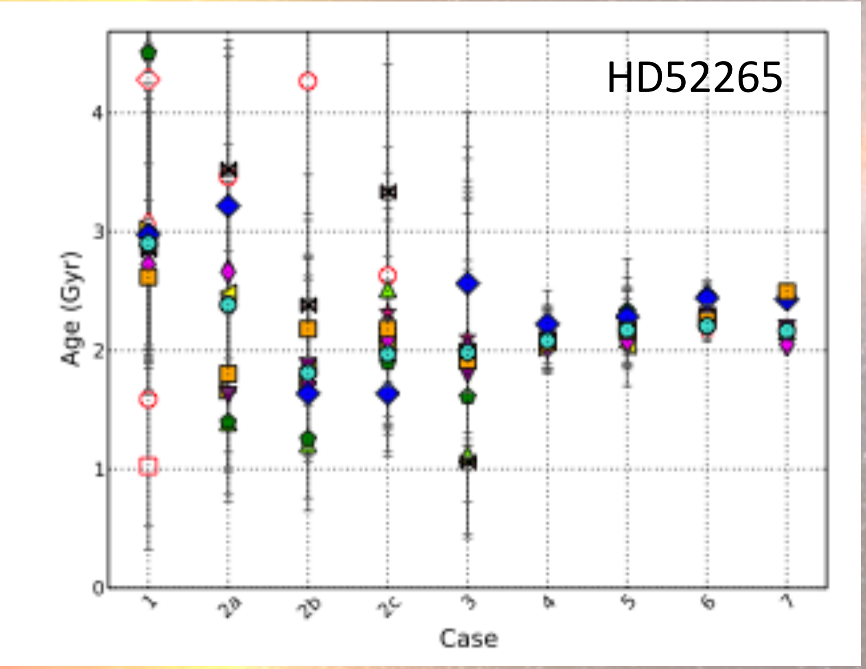
Deriving stellar parameters with seismology

- Scaling relations **[Kjeldsen & Bedding 1995]**

$$\frac{M}{\mathrm{M}_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{3/2}$$ (~5%)

$$\frac{R}{\mathrm{R}_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{1/2} .$$ (~10%)

- Best-fit model to spectroscopic and seismic constraints
  - Grid-based models **[e.g. Chaplin et al. 2014]**
  - “Boutique” modeling: e.g. Asteroseismic Modeling Portal **[Metcalfe et al. 2009]**



[Lebreton & Goupil 2014]

Stellar Modeling

- Stellar models:

Microphysics
  - Equation of state
  - Opacities
  - Nuclear reaction rates
  - Diffusion
  - Composition
  - Mixing length theory
  - Overshoot?
  - …

- Observables:
  - Spectroscopic: T_{eff}, Fe/H, log g, L
  - Seismic: $\Delta\nu$, ν_{max}, $\nu_{n,l}$

Find the best model that fits all the observables available

Stellar evolution codes

- A variety of codes for stellar modeling:
  - CESAM/CESTAM [Morel 1997; Marquez et al. 2013]
  - ASTEC [Christensen-Dalsgaard 2008]
  - MESA [Paxton et al. 2013]
  - STAREVOL [e.g. Palacios et al. 2013]
  - …
- Include some different physics:
  - Include or not microscopic diffusion?
  - Rotation?
  - Overshooting?
  - Helium treatment?

Grid-based modeling

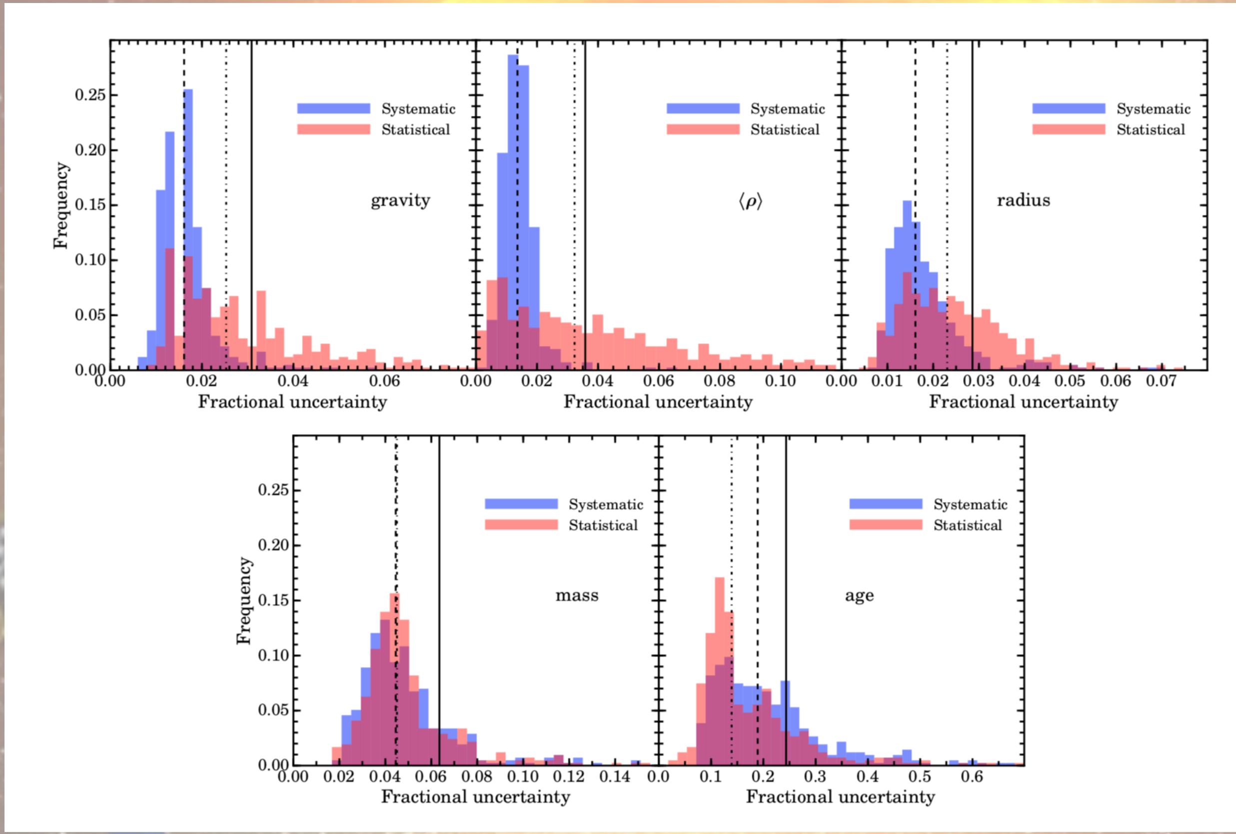
- Using a stellar evolution code:
  - create a a pre-calculated grid of models with a given resolution in metallicity and mass
- Fitting of:
  - spectroscopic observables
  - seismic observables (global parameters and/or frequency ratios and/or individual frequencies)
- Different statistical method:
  - a maximum likelihood approach (e.g. Stello et al. 2009; Basu et al. 2010)
  - a Bayesian approach (e.g. Silva Aguirre et al. 2016)

Grid-based modeling

- Analysis of 415 solar-like stars and subgiants observed in short cadence with *Kepler* **[Serenelli et al. 2017]**
- Spectroscopic observables from DR13 Apache Point Observatory Galactic Evolution Experiment (APOGEE):
  - T_{eff}
  - [Fe/H]
- Photometric T_{eff} also used for comparison
- Seismic observables from 30 to 1000 days of Kepler observations:
  - $\Delta\nu$
  - ν_{max}

Grid-based modeling

- GBM of the 415 stars from 7 pipelines and using different combinations of inputs



Median uncertainties of:
~2% in R
~5% in M
~20% in age
~3.5% in $< \rho >$

[Serenelli et al. 2017]

Grid-based modeling

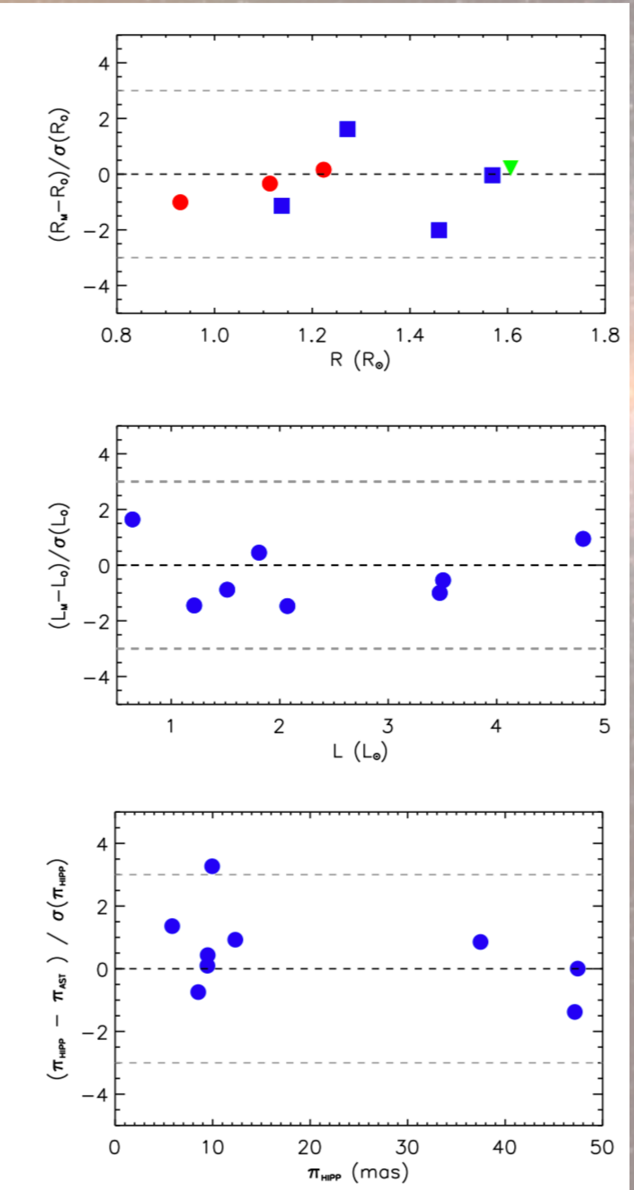
- Applied to planet-host stars [Silva Aguirre et al. 2015]
  - 33 Kepler Objects of Interest (KOI)
  - BAyesian STellar Algorithm (BASTA, based on the GARSTEC code) to fit T_{eff}, [Fe/H], frequency ratios (r_{01}, r_{02})
- Statistical uncertainties
  - 1.2% in R, 3.3% in M, 14% in age
- Quantification of the impact of input physics
  - Diffusion (~2%),
  - convective overshoot (<0.05% in age and mass)
  - mixing length and composition → smaller than statistical uncertainties
- Systematic uncertainties from different methods (YMCM, AMP)
  - <5% in R
  - <10% in M
  - <40% in age (AMP SBBN helium)

“Boutique” modeling

- Run a large number of models (~10^5) for a given star
- Asteroseismic Modeling Portal (AMP) **[Metcalfe et al. 2009]**
- Applied to a large sample of stars
  - Fitting individual frequencies and/or frequency ratios
  - Improved precision on M, R, age
    [Mathur et al., 2012; Metcalfe et al. 2014; Creevey et al. 2017]
  - Structure:
    - base of convection zone

“Boutique” modeling

- Analysis of 57 stars (planet hosts, binaries, solar-analogs, active stars)
- Fitting of spectroscopic observables and frequency ratios only
- Median uncertainties of
  - 1% in R
  - 3% in M
  - 7-11% in age
- Comparison of the asteroseismic results with independent measurements of radius, luminosity, and parallax:
  - Good agreement within less than 2 sigma



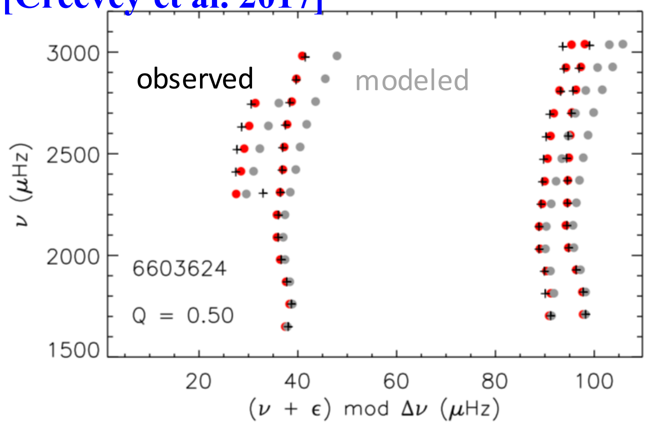
[Creevey et al. 2017]

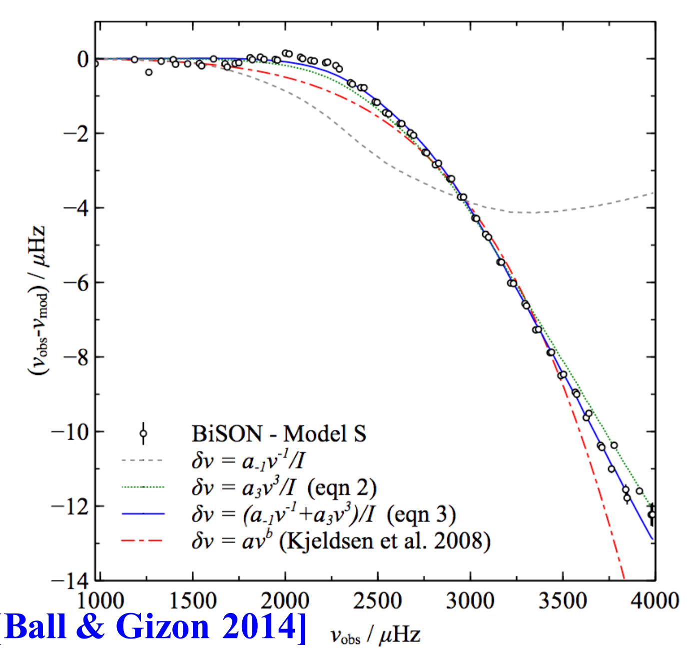
Some issues in the models…

'We're going to need a bigger rug or we're sunk.'

Some issues (1):
Surface effects

[Creevey et al. 2017]



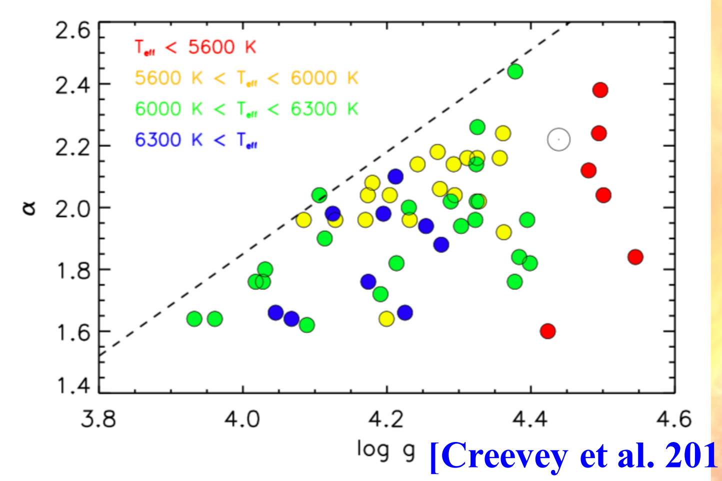


[Ball & Gizon 2014]

- Systematic difference between observed p-mode frequencies and modeled ones
  - Due to the surface layers that are not properly modeled
- Different ways to overcome it:
  - Surface term following the formula of **Kjeldsen et al. (2008)** or **Ball & Gizon (2014)**
  - Use frequency ratios insensitive of the surface effects
  - Use 3D simulations prescriptions by matching with 1D models **[Trampedach et al., 2017]**
- Recent work by **Basu & Kinnane (2018)** (use of BG14, frequency ratios, epsilon differences):
  - different corrections of the surface effects lead to robust estimates of M, R, age

Some issues (2):
Mixing Length Theory

- MLT from Bohm-Vitense (1958):
  - Bubbles of gas warmer than their surroundings and travel by one mixing length: $\ell = \alpha H_{\rm p}$
  - valid for most of convection zone that is very close to adiabatic
- Near the boundaries, this is not the case anymore
  - In particular the upper boundary: superadiabatic below photosphere



[Creevey et al. 2017]

- 3D radiative-coupled hydrodynamics simulations could be used as a constraint for the 1D models [Trampedach et al. 2014]

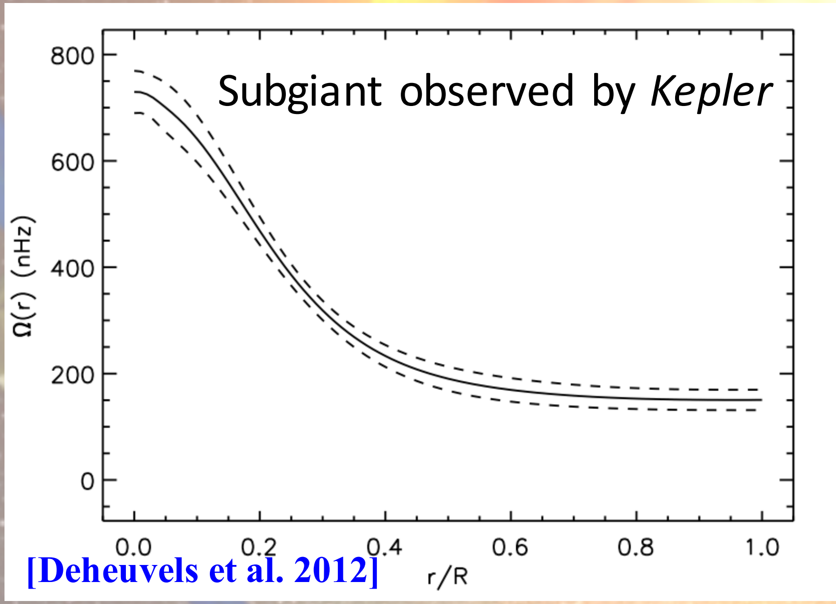
New constraints from asteroseismology

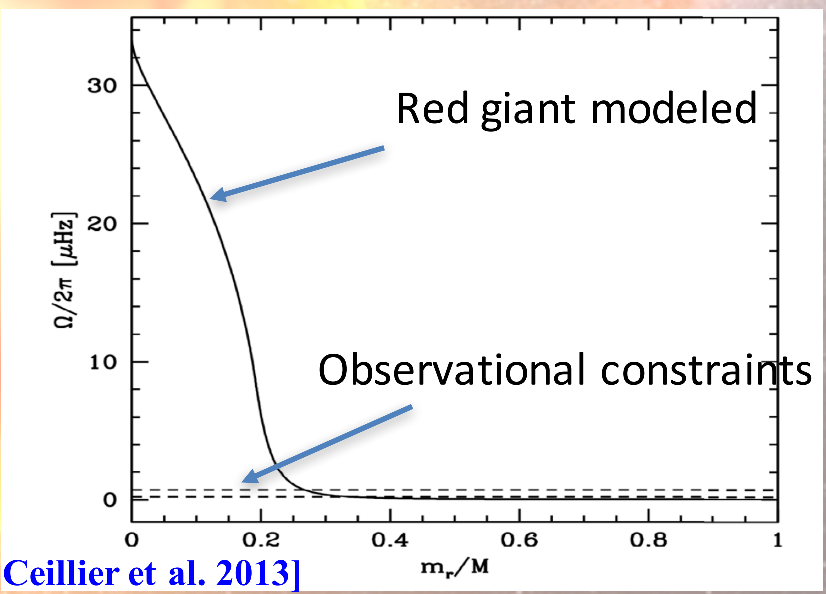
Constraints from asteroseismology

- Internal dynamics of subgiants and red giants
  - Rotation [Beck et al. 2012; Mosser et al. 2012; Deheuvels et al. 2012;2014]
  - Magnetic field [Fuller et al. 2016; Stello et al. 2016]
- Depth of convection zone and He ionization zone from acoustic glitches [e.g. Mazumdar et al. 2014]
- Convective cores detection, size estimation…[e.g. Deheuvels et al. 2016]
- Mass loss in red giants [e.g. Miglio et al. 2012]
- …

Internal rotation

- Rotational splittings measured in subgiants and red giants from the mixed modes
  - Core rotation estimate: core rotates faster than the surface)
  - Comparison with stellar evolution codes including rotation shows a disagreement (at least an order of magnitude)





Summary

- Stellar evolution codes based on the Sun
  - Not perfect agreement with helioseismology (surface abundances)
- But provide a good estimate of the stellar fundamental parameters
- Still need: physical processes missing or improvements
- Asteroseismology is providing constraints.
- What we expect with SONG observations?
  - Better understanding of the convection from simultaneous observations with photometric observations
  - Lower frequency modes
  - Bright stars: additional complementary observations to better test the models
  - Point the stars when we want and for the length of period we want:
    - Better characterization of the modes
    - Observations at different moments of magnetic activity of the stars (surface effects)
    - …

Thank you

smathur@iac.es

Convective core

- Frequency ratios r_{010} sensitive to the core structure:

$$d_{01}(n) = \frac{1}{8}(\nu_{0,n-1} - 4\nu_{1,n-1} + 6\nu_{0,n} - 4\nu_{1,n} + \nu_{0,n+1}) \quad (1)$$

$$d_{10}(n) = -\frac{1}{8}(\nu_{1,n-1} - 4\nu_{0,n} + 6\nu_{1,n} - 4\nu_{0,n+1} + \nu_{1,n+1}). \quad (2)$$

$$r_{01}(n) = \frac{d_{01}(n)}{\Delta\nu_1(n)}$$

$$r_{10}(n) = \frac{d_{10}(n)}{\Delta\nu_0(n+1)}$$

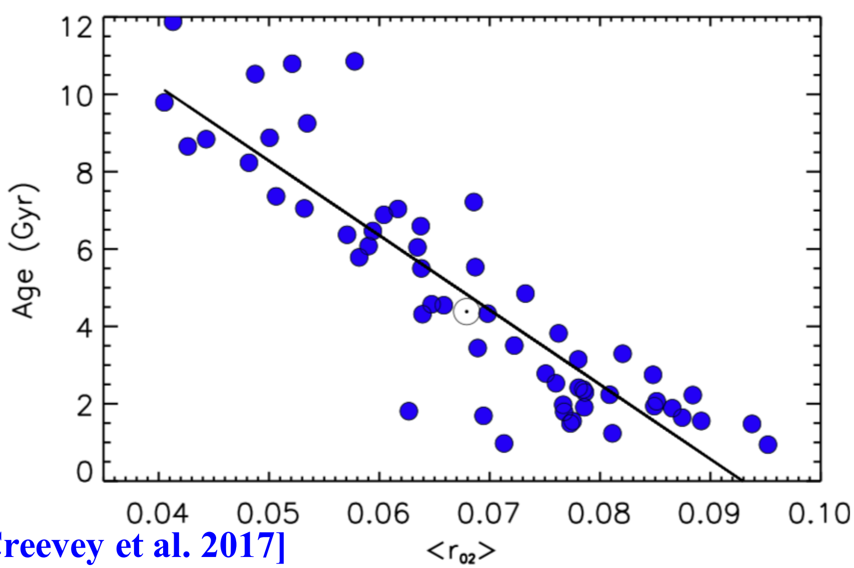
- instantaneous mixing beyond convective cores over a distance *d*ov taken as a fraction αov of the pressure scale height *H*P

Some trends

- Relation between age and frequency ratio r_{02}:

$$r_{02}(n) = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}},$$

  - sensitive to the gradient near the core



[Creevey et al. 2017]